1984

Load flow and contingency analysis in power systems

Kianfar Sorooshian
Portland State University

10.15760/etd.3310

An abstract of the thesis of Kianfar Sorooshian for the Master of Science in Electrical Engineering presented December 7, 1984.

Title: Load Flow and Contingency Analysis in Power Systems

Approved by members of the thesis committee:

[redacted]

Rajinder P. Aggarwal, Chairman

[redacted]

Faris Badi'i

[redacted]

Pieter A. Frick

[redacted]

James M. Heneghan

A load flow and contingency analysis program for secure design, planning and operation of power systems. Depending on the application either Newton-Raphson or Fast-Decoupled method is employed to solve the load flow. Fault analysis is done by Z bus method. Contingency analysis may be done following the load flow solution by Fast-Decoupled method. The program is also interfaced with a graphic system which displays a single line diagram of the system on the graphic screen along with relevant data and informs the operator of any change by flashing the faulted bus or the line outage.

LOAD FLOW AND CONTINGENCY ANALYSIS
IN
POWER SYSTEMS

by

KIANFAR SOROOSHIAN

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Electrical Engineering

Portland State University
1984

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of Kianfar Sorooshian presented December 7, 1984.

[redacted]

Rajinder P Aggarwal, Chairman

[redacted]

Faris Badi'i

[redacted]

Pieter A. Frick

[redacted]

James M. Heneghan

APPROVED:

[redacted]

Pieter A. Frick, Head, Electrical Engineering

[redacted]

Jim F. Heath, Dean of Graduate Studies and Research

TABLE OF CONTENTS

Page

LIST OF MAJOR SYMBOLS

a	=	Off-nominal transformer turn ratio
B	=	Imaginary part of bus admittance matrix [Y bus]
G	=	Real part of bus admittance matrix [Y bus]
$\bar{I}_{pq}$	=	Current flow into element pq
n	=	Total number of buses in the power system
P_{GP}	=	Real power generation at bus p
P_{LP}	=	Real power load at bus p
P_P	=	Net real power injected into bus p = $P_{GP}-P_{LP}$
Q_{GP}	=	Reactive power generation at bus p
Q_{LP}	=	Reactive power load at bus p
Q_P	=	Net reactive power injected into bus p = $Q_{GP}-Q_{LP}$
$\bar{V}$	=	n x 1 bus phase voltage vector
V_p	=	Voltage magnitude of pth bus
[Y bus]	=	n x n bus admittance matrix
$\bar{y}_{pq}$	=	$G_{pq} + jB_{pq}$ = pqth element of [Y bus]
$\bar{y}'_{pq}$	=	Total line charging admittance of line connected between p and q buses
$\bar{y}_{pp}$	=	Admittance of shunt element connected to bus p
θ_p	=	Phase angle of pth bus voltage
θ_{pq}	=	$\theta_p - \theta_q$ = phase angle difference between buses p and q.

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

As regards power network calculations performed by digital computer, the most widely employed are the "load flow" calculations. The power system state variables are the bus voltage magnitudes and phase angles and the unknown state variables can be obtained from the load flow. For off-line application, such as system planning and stability studies, the load flow solution programs usually employ Newton Raphson method (2.3) in conjunction with sparsity programming (if the network has more than a few hundred buses). The method has quadratic convergence, and for vast majority of practical power systems, has been found very reliable. However, the method does not have the speed needed for real time applications. For this purpose, there have been recent developments employing various decoupled methods. Various stages of development and contributions finally led to fast decoupled method [3], which is today widely recognized for its speed and good convergence characteristics, and is used in real time applications.

The concept of power system security has lately acquired prominence. It is an aid to power system operator to prevent the power system blackouts. The term that the power system is "secure" implies that not only are the present load requirements being met without any equipment overload or voltage problem, but it can also survive any reasonable future contingency without leading to equipment over-load, voltage degradation, system instability, service interruption, etc. This requires "security monitoring" of the present power system state and "contingency analysis" in real time.

Another problem which is of interest in real-time is the knowledge of power flow through various transmission lines and transformers for a fault somewhere on the system. Only three phase fault is considered, since it leads to maximum fault current. If the fault levels are too high, modification may be needed by shifting generation and/or transmission network.

CHAPTER II

LOAD FLOW STUDIES

2.1 INTRODUCTION

The solution of the load flow problem is carried out extensively on the digital computer for power system planning, operation and control. This is essential for both off-line applications, such as planning and stability studies and on-line applications, such as security monitoring and contingency analysis, optimal power flow, etc. An excellent review by Stott [4] gives the salient features and the comparative merits of different load flow solution methods. The important properties required of a load flow solution method are high computational speed, low storage requirements, reliable convergence and versatility. In this chapter, we shall define the load flow problem and discuss two methods of solution, viz., Newton Raphson and Fast Decoupled, which are presently almost always used by the industry. The sample IEEE 14 bus system is taken as an example and solved by both of these methods. All the data for this system is shown in Appendix D.

2.2 ANALYTICAL FORMULATION

The 3-phase power system is assumed to be balanced. Then the power network can be represented as a single phase system, with various elements represented by their positive sequence values. A bus is characterized by four variables, P, Q, V and θ, of which two are specified and the other two must be found. Depending upon which variables are specified, there are three types of buses:

1) Slack or swing bus with V, θ specified and P, Q unknown
2) P-Q bus with P,Q specified and V, θ unknown
3) P-V bus with P,V specified and Q, θ unknown

However, remembering that the state variables are V's and θ's, equations (B.1) and (B.2) give injected real and reactive power at each bus in term of V's and θ's and the elements of the bus admittance matrix (which is constant for given network). Then for each P-Q bus we have two unknowns (V and θ) and for each P-V bus one unknown (θ). Now we shall discuss Newton Raphson and Fast Decoupled methods as actual solution techniques.

2.3 NEWTON RAPHSON SOLUTION The mathematical procedure of Newton Raphson method is given in Appendix A.

Let n_1 = number of P-Q buses

n_2 = number of P-V buses

Then total number of buses is: $n = n_1 + n_2 + 1$

The problem is to find the unknown voltage magnitudes V (n_1 in number) at the P-Q and buses phase angle θ at P-Q and P-V buses. Let [x] be the vector of all unknown V's and θ's. From the set of equations (B.1) and (B.2), we select a number of equations equal to the number of unknowns in [x] to form the nonlinear algebraic equations [f(x)] = [y] similar to the set of equations (A.1).

$$[f(x)] = \left\{ \begin{array}{ll} \text{Eqs.} & \text{(B.1) and (B.2) for each P-Q} \\ & \text{and P-V bus} \\ \text{Eq.} & \text{(B.2) for each P-V bus} \end{array} \right\} = [y] \quad (2.1)$$

Notice that we have $2n_1 + n_2$ unknowns and $2n_1 + n_2$ non-linear algebraic equations to solve for them. The flow chart for the Newton Raphson Method is given in Appendix C.

An IEEE 14 bus test system (data in Appendix D) has been solved using the above method. The convergence criteria for both active and reactive power mismatch can be chosen by the user. Usually all unknown voltage magnitudes are chosen as 1.0 pu and all angles as zero degrees as starting values. This is called "Flat Start." The results of the load flow study are given in Appendix E. Typically, it takes 3 to 5 iterations to converge to the solution. A few observations about the data and results are in order:

(a) As seen from the data in Appendix D, the transformer tap setting may not be nominal value. A transformer with off-nominal turns ratio "a" can be represented by its admittance in series with an ideal auto transformer (9) as shown in Figure 1a.

The equivalent pi representation is shown in Figure 1b.

(b) Once the phasor bus voltages are known, line flows can be calculated. The current in the line pq from buses p towards q is given by

$$\bar{I}_{pq} = (\bar{V}_p - \bar{V}_q)\ \bar{y}_{pq} + \bar{V}_p\ \bar{y}'_{pq}/2 \qquad (2.2)$$

where $\bar{y}_{pq}$ = line admittance

$\bar{y}'_{pq}$ = line charging admittance

The complex power $P_{pq} + jQ_{pq}$ in the line pq from bus p towards bus q is given by

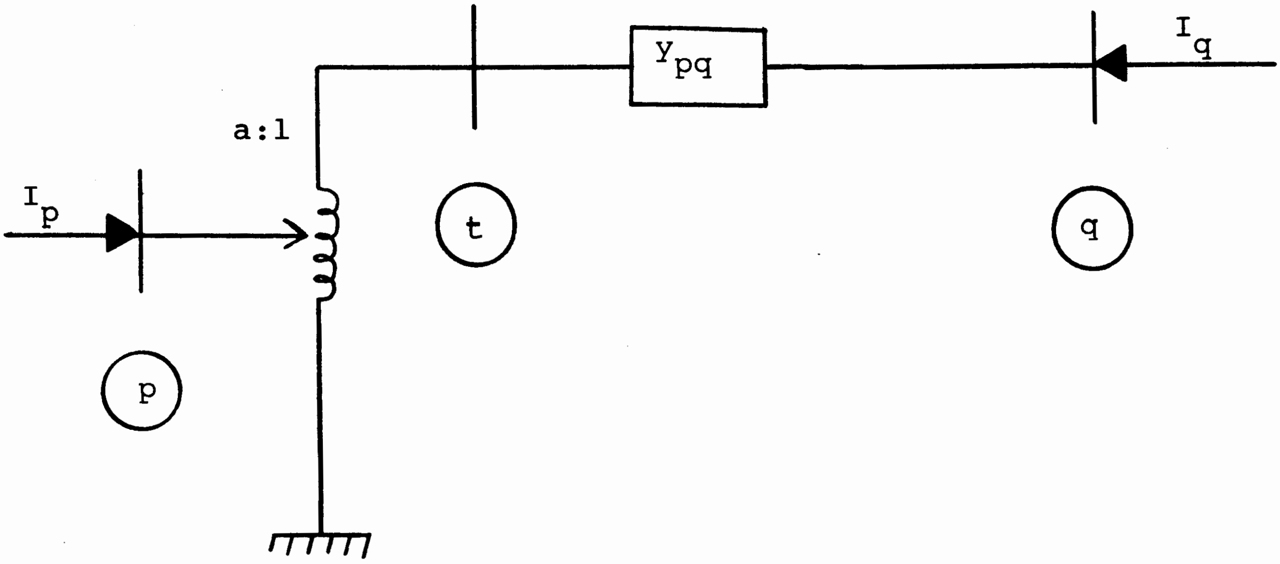
$$P_{pq} + jQ_{pq} = \bar{V}p\ (\bar{I}pq) \qquad (2.3)$$

Similarly at bus q, the power flow from bus q to p is

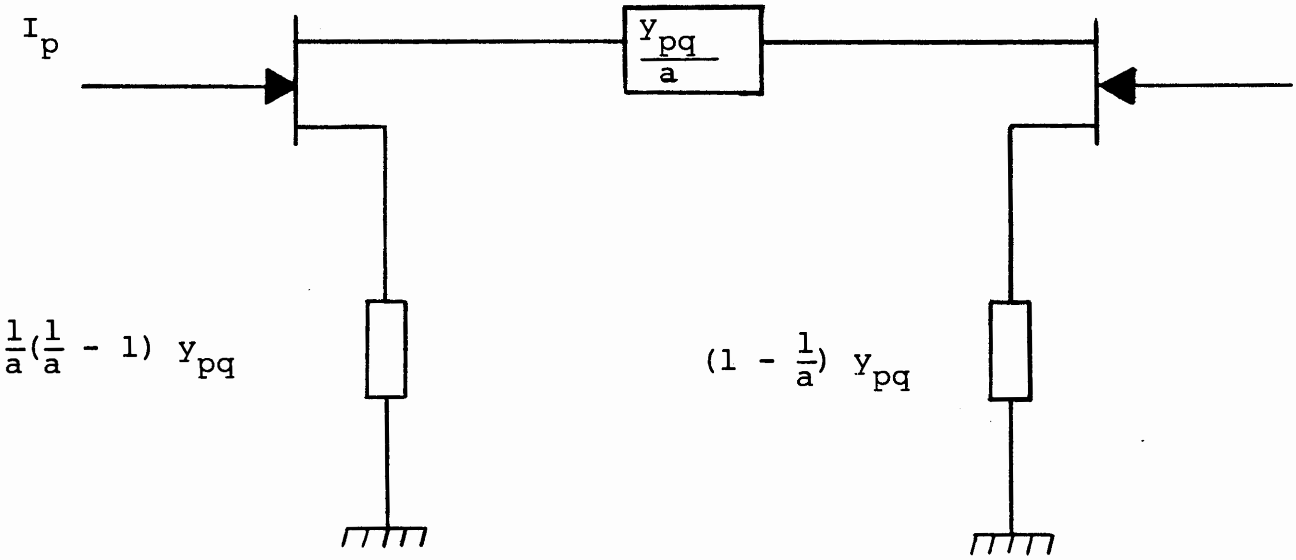
$$P_{qp} + jQ_{qp} = \bar{V}_q\ (\bar{I}_{qp}) \qquad (2.4)$$

where $\bar{I}_{qp} = (\bar{V}_q - \bar{V}_p)\ \bar{y}_{pq} + \bar{V}_q\ \bar{y}'_{pq}/2 \qquad (2.5)$

The power loss in the line p-q is the algebraic sum of powers determined from equations (2.3) and (2.4).



(a)



(b)

Figure 1. **Off-nominal ratio transformer representation (a) equivalent circuit (b) equivalent pi circuit.**

2.4 GRAPHICS

If a single line diagram of the system with all the pertinent load flow results is available, then it helps the system operator to make quick decisions for planning operation or control. Such a graphics capability has been built. The single line diagram shows the system layout, that is, the interconnection between different transmission lines, transformers and buses. It also shows different generators and loads. The numeric information displayed is real and reactive power flow for each generator, load and transmission line. It also displays the voltage magnitude and phase angle for each bus.

2.5 FAST DECOUPLED METHOD

The first step in applying the decoupling principle is to neglect the coupling submatrices [N] and [M] in equation (B.5) giving two separate equations

$$[\Delta P] = [H] [\Delta \Theta] \tag{2.6}$$

$$[\Delta Q] = [L] [\Delta V/V] \tag{2.7}$$

Equations (2.6) and (2.7) may be solved alternately as a decoupled set by Newton Raphron method, re-evaluating [H] and [L] after each iteration. In practical power systems, the following assumptions are valid

$$\text{CoS } \Theta_{pq} \quad 1 \ \& \ G_{pq} \sin \Theta_{pq} << B_{pq}$$

$$Q_p << B_{pp} V_p^2$$

Then in view of (B.7) and (B.8) and the above assumption, good approximations to (2.5) and (2.6) are

$$[\Delta P] = [V.B'.V]\ [\Delta\theta] \tag{2.8}$$

$$[\Delta P] = [V.B''.V]\ [\Delta V/V] \tag{2.9}$$

Where B' and B" are strictly elements of [-B], where [B] is the imaginary part of bus admittance matrix [Y bus].

Further simplification is made by taking left hand terms in (2.8) and (2.9) on to the left hand side of the equations and then in (2.9) removing the influence of MVAR flows on the calculation of [θ] by setting all the right hand terms to 1.0 pu. Then the final fast decoupled load flow equations become

$$[\Delta P/V] = [B']\ [\Delta\theta] \tag{2.10}$$

$$[\Delta Q/V] = [B'']\ [\Delta V] \tag{2.11}$$

Both [B'] and [B"] are real, sparse and contain only network admittances. They are constant and need to be inverted (or triangularized) only once at the beginning.

The recommended iteration scheme is to solve (2.10) and (2.11) alternately. Each iteration cycle comprises one solution for [Δθ] to update [θ] and then one solution for [ΔV] to update [V], termed as [1θ-1V] scheme.

Further modification which help in the convergence process are

(a) Omitting from [B'] the representation of those network elements that predominantly affect reactive flows, that is shunt reactances and shunt elements which arise in off-nominal ratio transformer representation.

(b) Doubling of the values of the shunt elements in the representation of [B"].

The flow chart for Fast Decoupled load flow is given in Appendix C.

The IEEE 14 bus solved earlier by Newton Raphron method is also solved by Fast Decoupled method and results given in Appendix E. The graphic display of the flow results is given in Fig. 2.

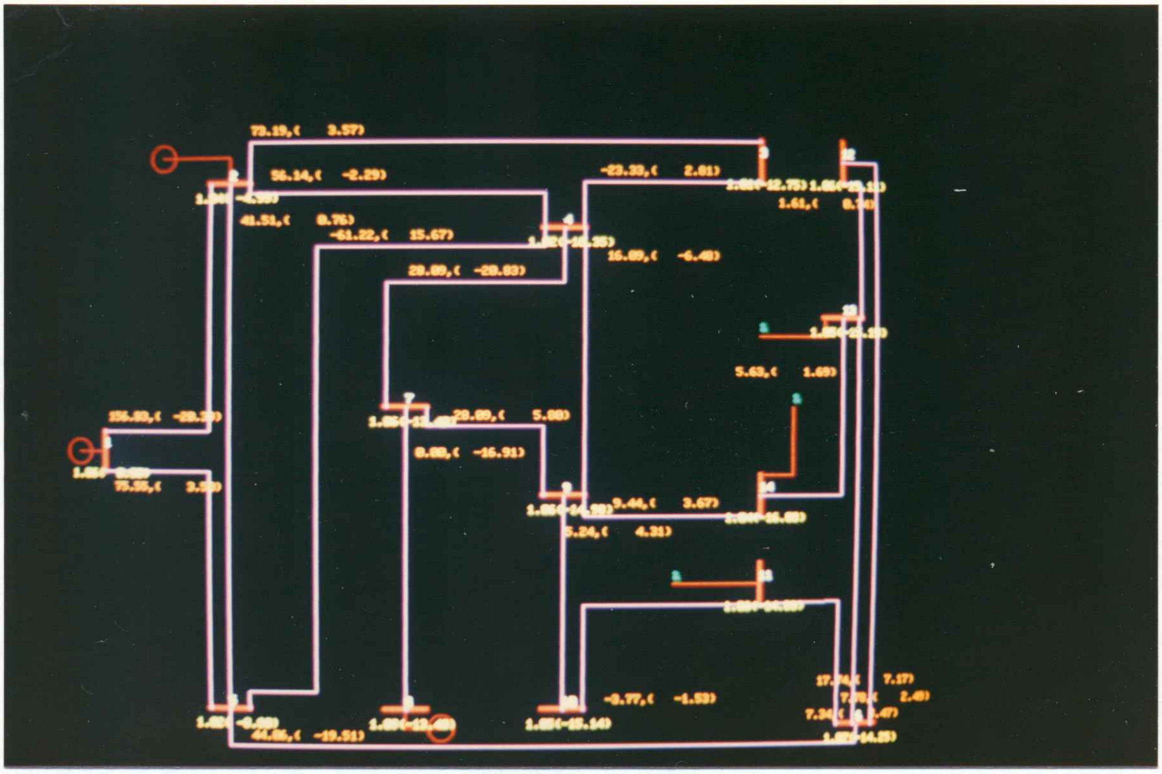


Figure 2. Graphic display of load flow for IEEE 14 bus system by Newton-Raphson method.

CHAPTER III

SYSTEM SECURITY AND CONTINGENCY ANALYSIS

3.1 INTRODUCTION

After the great 1965 blackout of the northeast, there has been increasing attention paid to the role of computers towards prevention of total or partial shut-down of the power systems [6]. In this context, we shall explain the concept of power system security and contingency analysis in this chapter. It is important that the computer programs which implement security related functions in real time be very fast to execute. We have also developed the graphic tools which not only show the system's present state, but also show the new system state for an assumed contingency.

3.2 SECURITY RELATED FUNCTIONS

First we shall define certain quantities related to power system security.

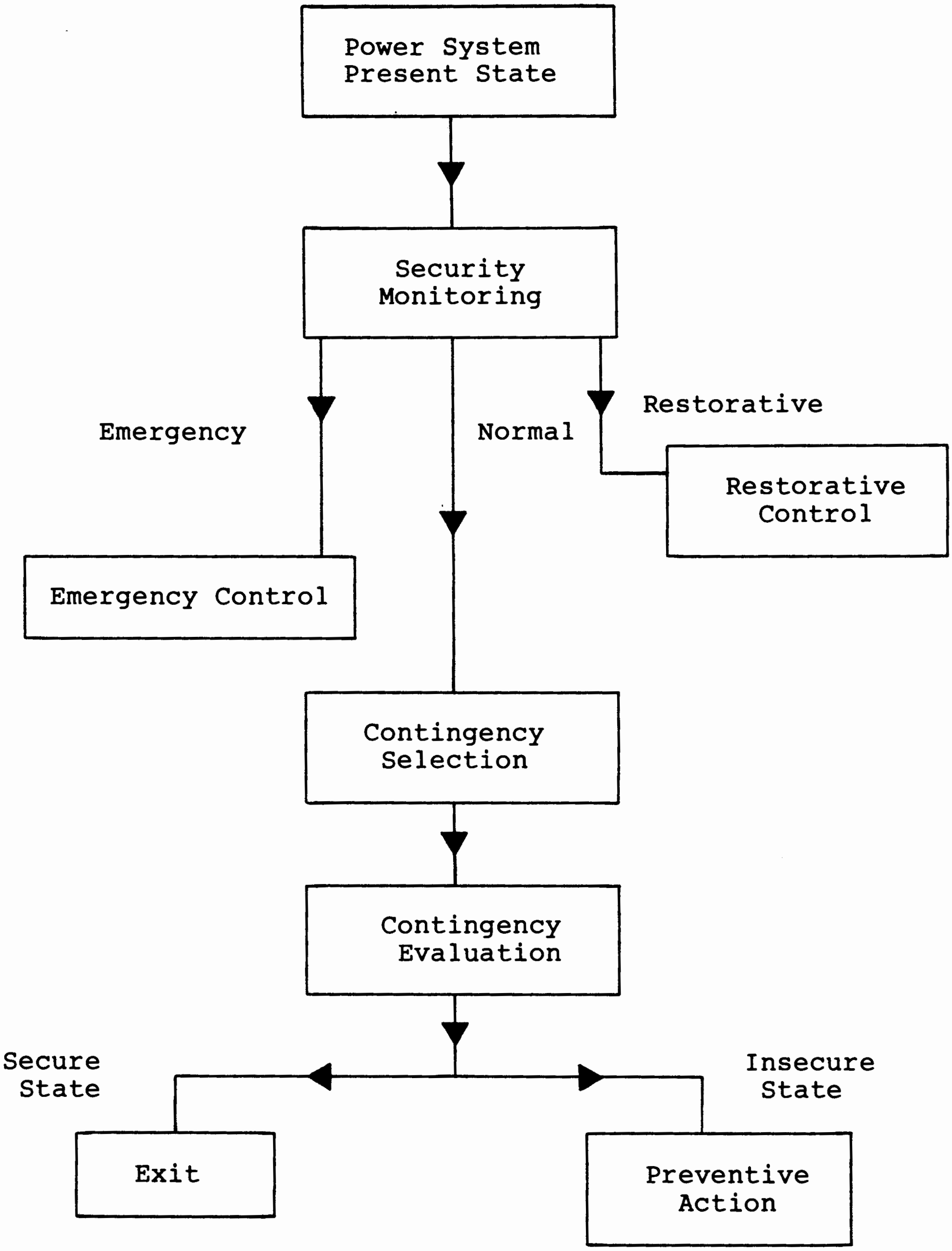
Normal State: A power system is in normal state if all the system loads are being met, no equipment such as generators, transformers and transmission lines etc. is overloaded, all bus voltages and system frequency are within specified limits, and the phase angle across any two connected buses is not too large (usually less than 45 degrees for stability considerations).

Emergency State: A power system is in emergency state if all the system loads are being met, but there is one or more problems due to equipment overload, by voltages and systems frequency not being within specified limits or phase angle difference across any two connected buses is too large.

Restorative State: A power system is in restorative state when all the system loads are not being met. It implies a partial or total shut down of the system. The main concern then is to restore all the system loads with as little delay as possible.

Figure 2 shows the basic functions of security control. As we start from the top down, we assume that the present power system state is available from the real time data. Then we perform "security monitoring" which is the on-line identification of the actual operating conditions of a system by checking the real time state to determine whether it is in a normal, emergency or restorative state.

If SM finds the system to be in an emergency or near emergency state, corrective action via "emergency control" may be extended manually or automatically depending upon the severity of the emergency. If it is not very critical, corrective action may be achieved by shifting generation from units in trouble to other available units. Severe steady state emergencies may require immediate load



<u>Figure 3</u>. Security Control Functions.

shedding. This can be done manually by supervisory control or automatically by the computer. If the overload is very slight, the operator may decide to ride it out, as the system loading may be decreasing or there may be ample time for field maneuvers to relieve the overload.

If the system is in emergency state, control is achieved almost completely by manual action. The restoration requires an orderly, coordinated procedure of bringing up generation, putting the transmission back together and picking up load--all in steps and at such a pace that dynamic imbalances in generation versus loud and constrictions in transmission capability would not occur to take the system back down again. To carry out this process, the operator would use the security monitoring function to keep track of what the system is doing in terms of status, power flows, voltages and frequency.

If the power system is found to be in the normal state by the SM procedure, the "security analysis" (SA) function is invoked to check on its security level. SA consists of a "contingency evaluation" program, which basically answers the question "what if a next contingency out of a set of possible contingencies takes place?" If the system stays in a normal state even after the contingency occurs, then it is in a "secure" state. However, if the system goes into an emergency or restorative state if the contingency did actually occur, then it is in "insecure" state. Preventive action may require strengthening the transmission network by putting more lines in service, adding generation, or changing the power flows by appropriate switching or putting the operator in an "alert" state to shed some loads if the contingency did occur. The last measure is to minimize the damage to the power system.

3.3 CONTINGENCY ANALYSIS

The contingencies may be grouped into two broad categories: (a) power outage and (b) network outage.

The power outage includes:

(i) Loss of generating unit.

(ii) Sudden change in load which may cause stability or oscillation problems.

(iii) Sudden change of power flow in an intertie, which implies sudden gain of generation for one area and loss of generation in the other area.

The most serious case from the point of view of steady state security is the loss of generation. The real power lost is distributed to a number of regulating generators according to an assigned set of distribution factors. However, if the generation is not available, then load shedding will have to be performed and the power system is in insecure state.

The network outage includes:

(i) Outage of a transmission line.

(ii) Outage of a transformer.

The system operator is interested to know if a network outage will lead to emergency or restorative state implying that the present state is insecure.

It is obvious that since the contingency analysis is performed in real time, the procedure must be computationally fast. For this purpose an adaptation of the fast decoupled method [3] and matrix inversion technique [11] is used. Recall equations (2.10) and (2.11) given below

$$[\Delta P/V] = [B'] \; [\Delta\theta] \tag{3.1}$$

$$[\Delta Q/V] = [B''] \; [\Delta V] \tag{3.2}$$

Experiments have shown that it is adequate to remove the series susceptence of the transmission line or transformer from [B'] and [B"]. Shunt susceptence either due to line charging or off-nominal transformer representation need not be removed from [B'] and [B"]. All outages must, of course, be reflected correctly in the calculation of (P/V and Q/V).

Let (3.1) or (3.2) be represented with base care (present state) or

$$[R] = [B_0] \; [E_0] \tag{3.3}$$

for which a solution

$$[E_0] = [B_0]^{-1} \; [R] \tag{3.4}$$

can be obtained by finding $[B_0]^{-1}$ (or equivalently by LU factors of $[B_0]$). As pointed out earlier, the outage of a transmission line or transformer can be reflected in $[B_0]$ by the series susceptence only. If the element between buses p and q is removed, then at most, two elements are modified in row p and two in row q of $[B_0]$. The outage matrix is then

$$[B_1] = [B_0] + b[M]^T [M] \tag{3.5}$$

when b = line or transformer series susceptence

[M] = row vector which is null except for $M_p = a$ & $M_q = -1$, where a = off nominal turns ratio referred to the bus p for a transformer and a = 1 for transmission line.

Depending upon the type of connected buses, only one row either p or q might be present in [B'] or [B"] in which case either M_p or M_q above are zeros or appropriate. If both the connected buses are P-V or slack, then [B"] requires no modification.

From (3.5), $[B_1]^{-1}$ is given by

$$[B_1]^{-1} = \{[B_0] + b [M]^T [M]\}^{-1} \tag{3.6}$$

It can be shown that [3, 11]

$$[B_1]^{-1} = [B_0]^{-1} - C [x] [M] [B_0]^{-1} \tag{3.7}$$

where $C = (1/b + [M] [X])^{-1}$ and $[X] = [B_0]^{-1} [M]^T$ (3.8)

The solution vector $[E_1]$ for the outage problem is

$$[E_1] = [B_1]^{-1} R \tag{3.9}$$

In view of (3.4) and (3.7), we can write (3.9) as

$$[E_1] = [E_0] - C [x] [M] [E_0] \tag{3.10}$$

Thus for each outage of a series branch, two vectors [X'] and [X''] must be calculated each requiring $[B'_0]^{-1}$ and $[B''_0]^{-1}$ which are already available from the base case solution.

The method outlined above can also be used for multiple outages, when the above procedure is applied recursively. The solution vector [E] is corrected successively as the effect of each branch outage is introduced one at a time. Although this method avoids the reinversion of [B], it is faster for at the most three simultaneous-outaged branches.

3.4 RESULTS

Appendix F.1 gives results for a line outage between bus #4 and 7 for the IEEE 14 bus system using the fast contigency analysis technique outlinged above. Appendix F.2 gives results for the same outage using Fast Decoupled Method. If we compare the results, significant error (which is still less than 2 MW) is found at buses 4 and 7. The results were compared with other outages as well (not reported) and the error found to be well within acceptable limits.

3.5 GRAPHICS

As in the case of load flow studies, the contingency study results are also displayed on single line diagrams. The line which is assumed to be out of service blinks on the display. All the numeric values displayed are as in the load flow results with the lint outage included. After the results have been studied, the system is restored to the pre-outage state, ready for further outage studies if needed.

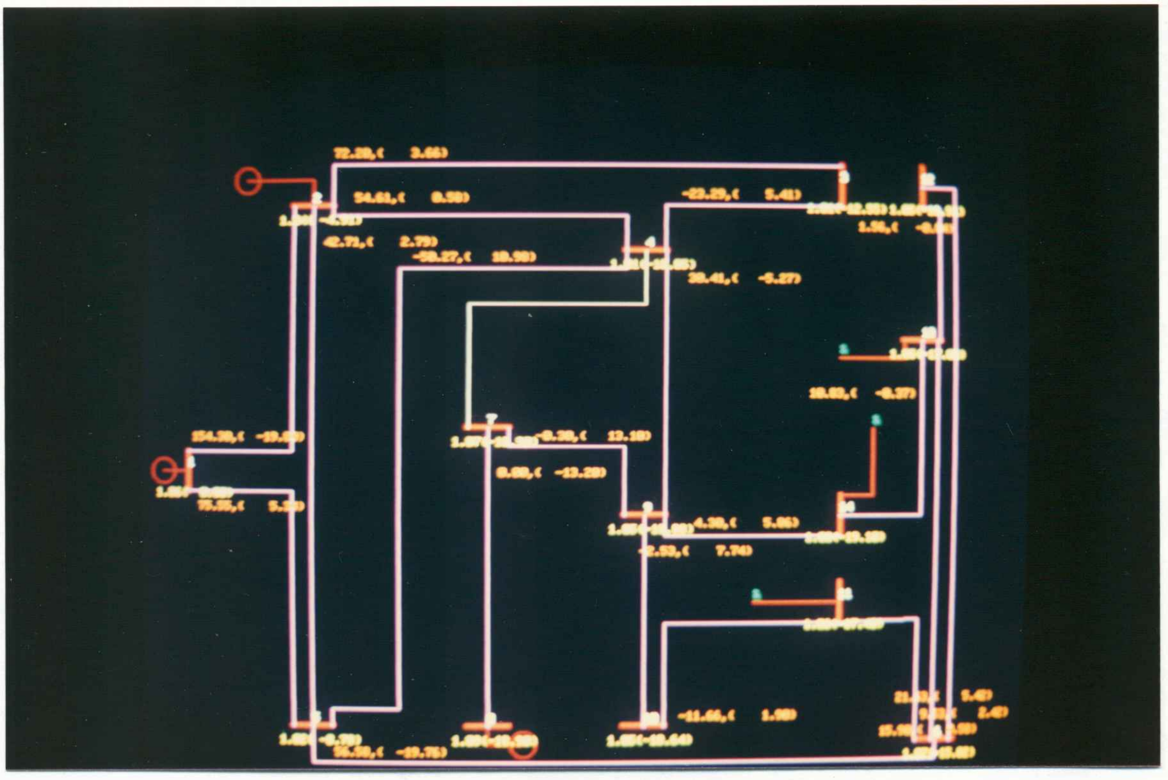


Figure 4. Graphic display of contingency analysis for IEEE 14 bus system (Line outage from bus 4 to bus 7).

CHAPTER IV

FAULT STUDIES

4.1 INTRODUCTION

When an abnormal condition arises in a power system such as a fault, in particular three phase faults, high currents flow in the system. The knowledge of magnitude of short circuit (current) level through equipment such as transformers and transmission lines is important to prevent damage due to undue heating and resulting electromechanical forces. This information is also needed to determine the interrupting rating of the circuit breakers, and relay co-ordination studies.

We shall study only three phase faults as they normally lead to maximum fault current.

4.2 PHYSICAL ASSUMPTIONS

Analysis is done on the basis of a study state AC model by representing the generators as constant voltage sources in series with appropriate machine reactance, usually subtransient if initial fault current is to be determined. Further simplifying assumptions are made as follows: (1) The normal loads, line charging capacitances and other shunt corrections to ground are neglected. This is based on the fact that the fault circuit has a much lower impedance than the shunt impedances. (2) All the transformers are considered to be at their nominal taps. Thus shunt elements which arise due to off-nominal representation are neglected. (3) Since all loads are neglected, the internal voltage of all generators must be equal and is usually taken equal to 1.0 pu.

4.3 SYMETRICAL THREE PHASE FAULT ANALYSIS

We assume that the network is balanced with all the source (generator) voltages also balanced. Then with symetrical three phase faults with or without ground, balanced conditions still exist. Analysis can be carried out on the basis of a per phase equivalent involving positive sequence impedances, voltages, and currents.

Let the power system network consist of n buses and the neutral bus denoted by O, as shown in Figure 5. The network consists of positive sequence impedances only.

There is no loss of generality if we assume that the first m buses are those where generators are connected. The generator representation consists of a constant voltage source (positive sequence value) in series with subtransient reactance X''_g if we are interested to know initial (maximum) fault current level. Since by assumption all these voltage sources are equal (value assumed 1.0 pu), we augment the first m buses by generator subtransient reactances connected to a common fictitious node O' and the common positive sequence generator voltage source V_0 is connected between O' and neutral O.

If there is a three phase fault at bus p, then there will be additional bus current I_{pf} as shown in Figure 3. Since the network is linear, we can apply superposition. Bus Voltages during fault = Bus voltages prior to the fault

+ Bus voltages due to I_{pf} alone (4.1).

All bus voltages prior to fault are equal to generator voltage V_0 since there are no shunt connections and hence no line flows.

If $[Z_{bus}]$ is the n x n bus impedance matrix with all generator voltages V_0 reduced to zero and neutral O as reference less than bus voltages due to I_{pf} alone are $[Z_{bus}]$ * [I], where [I] is n x 1 vector with all elements as zero except for the p^{th} element whose value is I_{pf} or $-I_f$.

If we employ subscript 'f' to indicate during fault and '0' prior to the fault, then bus voltages after the fault occurs are given by

$$V_{if} = V_0 - Z_{ip} I_f \qquad (4.2)$$

$$i = 1,2,...n$$

where Zip is the (i,p)th element of Z_{bus}

$$\text{Now } V_{pf} = V_0 - Z_{pp} I_f \qquad (4.3)$$

$$\text{But } V_{pf} = V_f = z_f I_f \qquad (4.4)$$

where z_f = Fault impedance

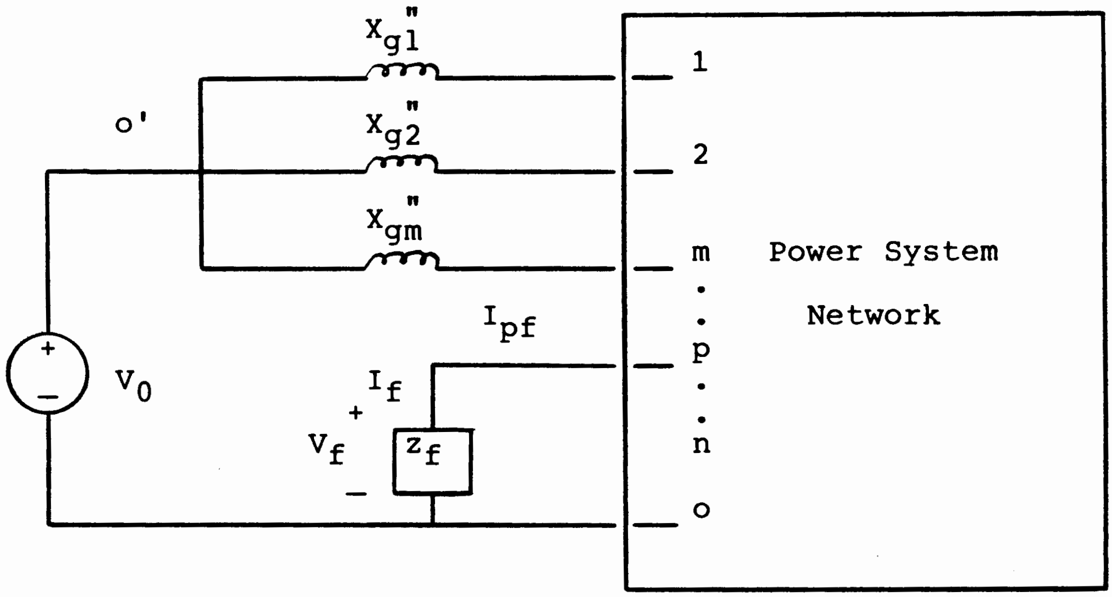


Figure 5. Power system representation for a symmetrical three phase fault at bus p.

From (4.3) & (4.4)

$$I_f = \frac{V_0}{Z_{pp} + z_f} \tag{4.5}$$

$$V_{pf} = z_f * I_f = z_f * (Z_{pp} + z_f)^{-1} * V_0 \tag{4.6}$$

$$V_{if} = V_0 - Z_{ip} * (Z_{pp} + z_f)^{-1} * V_0 \quad \begin{matrix} i = 1,2\ldots n \\ i \neq p \end{matrix} \tag{4.7}$$

Equation (4.5), (4.6) and (4.7) enable us to calculate the fault current I_f and voltage at all buses including the faulted bus. Remember that z_f is the fault impedance between each phase and neutral. Any impedance between neutral and ground would not change the results since there are no zero sequence currents for a balanced three phase system.

As seen from (4.5) to (4.7), the only information we need to calculate fault currents and voltages in the bus impedance matrix $[Z_{bus}]$ for the positive sequence network which includes generator reactances. This can be obtained by inversion of the bus admittance matrix $[Y_{bus}]$. However, $[Y_{bus}]$ is a very sparse matrix while Z_{bus} is a full matrix. This could cause storage problems if the number of buses is large (say greater than 100) and it is not recommended to form the full $[Z_{bus}]$ matrix. We note from (4.5) to (4.7) that for the fault at p^{th} bus, we require only p^{th} column of $[Z_{bus}]$. This may be obtained quite readily if the LU factors of $[Y_{bus}]$ are available. Consider the set of n simultaneous linear algebraic equations

$$[Y_{bus}][X] = [b] \tag{4.8}$$

when $[Y_{bus}]$ is n x n matrix while [X] and [b] are n x 1 vectors. If we solve for [X] with all elements of [b] as zero except for the p^{th} element which is 1.0, then [X] will be the p^{th} column of $[Z_{bus}]$.

Once the voltages during the fault are known, current through any element kl can be found. If y_{kl} is the admittance of the element

$$i_{kl} = (V_{kp} - V_{lp})\, y_{kl} \tag{4.8}$$

To find current by a generator connected to bus k we have

$$i_{gk} = (V_0 - V_{kp})\, y_{kg} \tag{4.9}$$

where V_0 is the internal voltage of the generator ($= 1.0 \angle\theta$) and y_{kg} is the subtransient admittance of the generator connected to bus K. The flow chart for the fault studies is given in Appendix C.

4.4 RESULTS

The results for a 3 phase fault at bus #5 for the IEEE 14 bus system are shown in Appendix G. The voltage magnitude and phase angle for all the buses and the current flow in all the lines is given. The same results are also displayed on the single line diagram, where the faulted bus is shown blinking (Fig. 6).

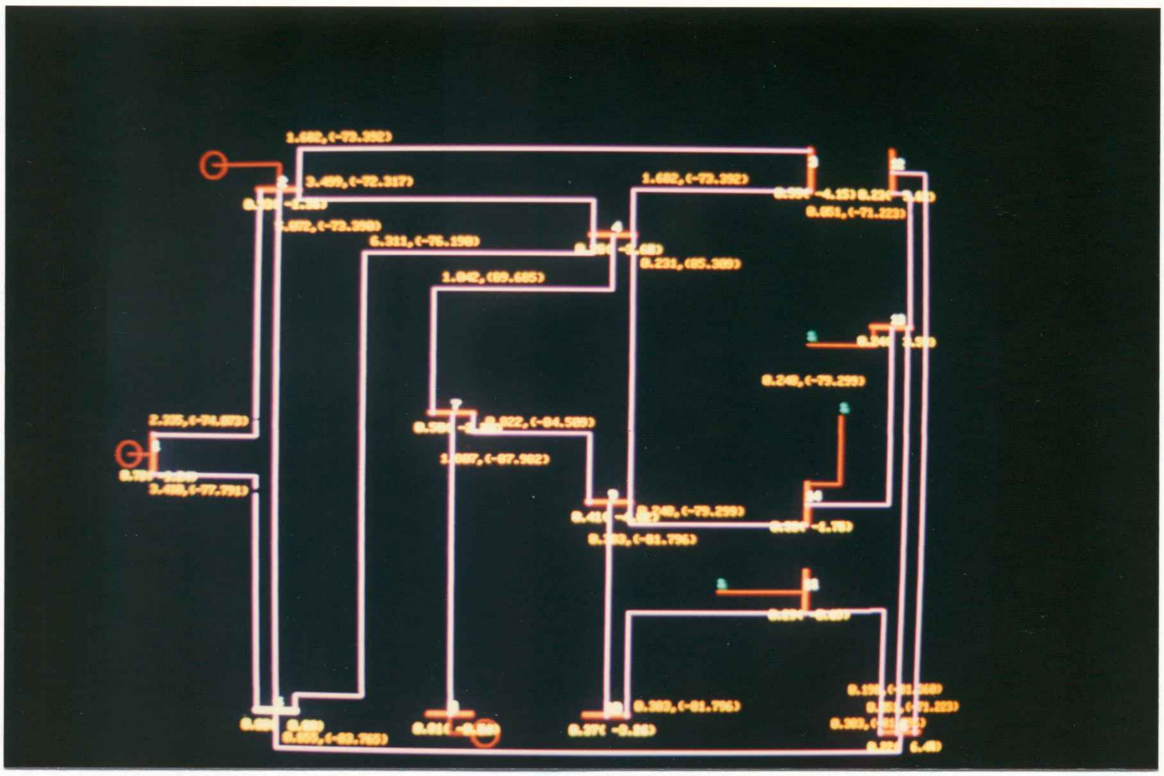


Figure 6. Graphic disply of fault studies for IEEE 14 bus system (fault at bus 5).

CHAPTER V

COMPUTER PROGRAM

The program is written using both the Shell script and C computing languages, compiled and run by Unix operating system on a VAX 11/750 computer. It includes code in Shell which is for command subprogram and code in 'C' for the purpose of data file creation, computation and graphics.

The user oriented features of the program are shown in the flow chart which is given in Appendix H. An effort has been made to make the program as easy to use as possible for the user and simulate the real-time environment for which it is intended.

With reference to the flow chart, the program asks the user to input the name of the output file where the results are to be stored. If such a file name already exists in the directory, another name has to be selected. Next the user has the option to use an already existing input data file or to create one interactively.

The input data file consists of the computation data (maximum mismatch error maximum number of iterations allowed and base MVA). Line data (number of lines, line designation, resistance and reactance in p.u. and half line charging * line in p.u.), bus data (bus number, generation and load power in MW and MVAR) and transformer data (transformer designation, impedance and tap setting), regulated bus (P-V bus) data (voltage in p.u.), shunt elements data (bus number and the shunt value) and the graph data which is used to layout a single line diagram of the system. Graph data includes coordinates of locations of generation stations and loads, coordinates and slope of each bus and also the coordinates of the path of lines.

After the creation of the input data file there are three possible paths for the user to follow which are summarized below.

Path 1: Load flow solution is obtained by Newton Raphson Method, after which the results are stored in the designated output file as well as displayed on the screen. After that the results are also shown on the single line diagram. The user has further option to study a three phase fault at any bus.

Path 2: This path is chosen when only fault studies have to be made. The results are stored in the designated output file as well as displayed on the screen. However, this path does not create the single line diagram and as such may not be favored by the user.

Path 3: Load flow solution is obtained by Fast Decoupled Method and results stored and displayed as in path 1. This is a necessary path to follow if we wish to perform contingency analysis. However, contingency analysis may be completely skipped if desired. After this the path also directs us to fault studies if desired.

The exact format of the input data and the program listing are provided in a separate user's manual. This manual also gives technical information on Shell command subprogram and 'C' language data file creation, computation and graphics programs.

The program has the capability to study a system where the maximum bus number is 32 and line number is 64. However, this capability can be increased by modifying the dimension statements in the program.

BIBLIOGRAPHY

1. W.F. Tinney and C.E. Hart, "Power Flow Solution by Newton's Method" IEEE Trans, PAS. Vol. 86, pp. 1449-60, Nov. 1967.

2. B. Stott, "Decoupled Newton Load Flows" IEEE Trans, PAS, Vol. 91, pp. 1955-1959, Sept/Oct 1972.

3. B. Stott and O. Alsac, "Fast Decoupled Load Flow" IEEE Trans, PAS, Vol. 93, pp. 859-869, May/June 1974.

4. B. Stott, "Review of Load Flow Calculation Methods" Proc, IEEE, Vol. 62, pp. 916-929, July 1974.

5. Tomas E. Dy Liacco, "System Security: The Computer's Role" IEEE Spectrum, pp. 43-50, June 1978.

6. Tomas E. Cy Liacco, "An Overview of Power System Control Centers" IEEE Tutorial Course, pp. 5-16, July 1977.

7. S.N. Talukdar and F.F. Wu, "Computer Aided Dispatch for Electric Power Systems" Proc. of the IEEE, Vol 69, pp. 1212-1231, Oct. 1981.

8. W.F. Tinney and J.W. Walker, "Direct Solutions of Sparse Network Equations by Optimallyu Ordered Triangular Factorization: Proc. of the IEEE, pp. 1801-1809, Nov. 1967.

9. G.W. Stagg and A.H. El-Abiad, "Computer Methods in Power Systems Analysis" (Book), McGraw-Hill, 1968.

10. M.A. Pai, "Computer Techniques in Power System Analysis" (Book), McGraw-Hill, 1979.

11. J.M. Ortega and W.C. Rheinbold, "Iterative Solutions of Linear Equations in Several Variables" (Book) Academic Press, 1970.

APPENDIX A

NEWTON RAPHSON METHOD

Newton Raphson Method for Solution of Non Linear Algebraic Equations.

Given a set of non linear algebraic equations:

$$
\begin{aligned}
f_1(x_1,x_2,..,x_n) &= y_1 \\
f_2(x_1,x_2,..,x_n) &= y_2 \\
&\vdots \\
f_n(n_1,n_2,..,x_n) &= y_n
\end{aligned}
\tag{A.1}
$$

We want to solve for the unknowns x_1, $x_2,..,x_n$. Let the initial estimate be x_1^o, $x_2^o,..,x_n^o$. An approximate correction vector $[\Delta x]$ whose components are $\Delta x_1, \Delta x_2,.., \Delta x_n$ is given by

$$
\begin{bmatrix}
\partial f_1/\partial x_1 & \partial f_1/\partial x_2 & ..\partial f_1/\partial x_n \\
\partial f_2/\partial x_1 & \partial f_2/\partial x_2 & ..\partial f_2/\partial x_n \\
\vdots & & \\
\partial f_n/\partial x_1 & \partial f_n/\partial x_2 & ..\partial f_n/\partial x_n
\end{bmatrix}
\begin{bmatrix}
\Delta x_1 \\ \Delta x_2 \\ \\ \Delta x_n
\end{bmatrix}
=
\begin{bmatrix}
y_1-f_1(x_1^o,x_2^o,..,x_n^o) \\
y_2-f_2(x_1^o,x_2^o,..,x_n^o) \\
\vdots \\
y_n-f_n(x_1^o,x_2^o,..,x_n^o)
\end{bmatrix}
\tag{A.2}
$$

or in vector notation

$$[J]\ [\Delta x] = [\Delta y] \tag{A.3}$$

where $[J]$ is the Jacobian and is computed at $x_1^o, x_2^o,..,x_n^o$. $[\Delta y]$ is the error vector. Then

$$[\Delta x] = [J]^{-1}\ [\Delta y] \tag{A.4}$$

The corrected vector $[x^1]=[x^o]+[\Delta x]$ becomes the first estimate. We reiterate until convergence is obtained which is assumed when all y's are less than a small preassigned value.

APPENDIX B

POLAR POWER MISMATCH

The complex injected power $P_p + Q_p$ injected at bus p is given by

$$P_p + jQ_p = \bar{V}_p \bar{I}_p^* = \bar{V}_p \left[\sum_{q=1}^{n} Y_{pq} V_q \right]^*$$

then
$$P_p = V_p \sum_{q=1}^{n} V_q (G_{pq} \mathrm{COS}\ \theta_{pq} + B_{pq} \mathrm{SIN}\ \theta_{pq}) \tag{B.1}$$

$$Q_p = V_p \sum_{q=1}^{n} V_q (G_{pq} \mathrm{SIN}\ \theta_{pq} - B_{pq} \mathrm{COS}\ \theta_{pq}) \tag{B.2}$$

For assumed values of V's and θ's, the power mismatch at bus p is given by

$$\Delta P_p = P_p^{sp} - P_p \tag{B.3}$$

$$\Delta Q_p = Q_p^{sp} - Q_p \tag{B.4}$$

where P_p^{sp} and Q_p^{sp} are scheduled or specified real and reactive power injections at bus p.

From Appendix A, the Newton Raphron algorithm is

$$\begin{vmatrix} H & N \\ M & L \end{vmatrix} \begin{vmatrix} \Delta\theta \\ \Delta V/V \end{vmatrix} = \begin{vmatrix} \Delta P \\ \Delta Q \end{vmatrix} \begin{matrix} \text{for all P-Q and P-V buses} \\ \text{for all P-Q buses} \end{matrix} \tag{B.5}$$

where [Δθ] and [ΔV] are angle and voltage corrections. Notice that the correction vector [ΔV] is divided by [V] as this simplifies expressions for the elements of the Jacobian given below and is also known to help in faster convergence. It can be easily shown that for $p \neq q$

$$H_{pq} = L_{pq} = V_p V_q (G_{pq} \mathrm{SIN}\ \theta_{pq} - B_{pq} \mathrm{COS}\ \theta_{pq}) \tag{B.6}$$

$$N_{pq} = -M_{pq} = V_p V_q (G_{pq} \mathrm{COS}\ \theta_{pq} + B_{pq} \mathrm{SIN}\ \theta_{pq}) \tag{B.7}$$

for $p = q$

$$H_{pp} = -Q_p - B_{pp}V_p^2 \tag{B.8}$$

$$L_{pp} = Q_p - B_{pp}V_p^2 \tag{B.9}$$

$$N_{pp} = P_p + G_{pp} V_p^2 \tag{B.10}$$

$$M_{pp} = P_p - G_{pp} V_p^2 \tag{B.11}$$

APPENDIX C

FLOW CHARTS

This appendix gives the flow charts for load flow, contingency analysis and fault studies.

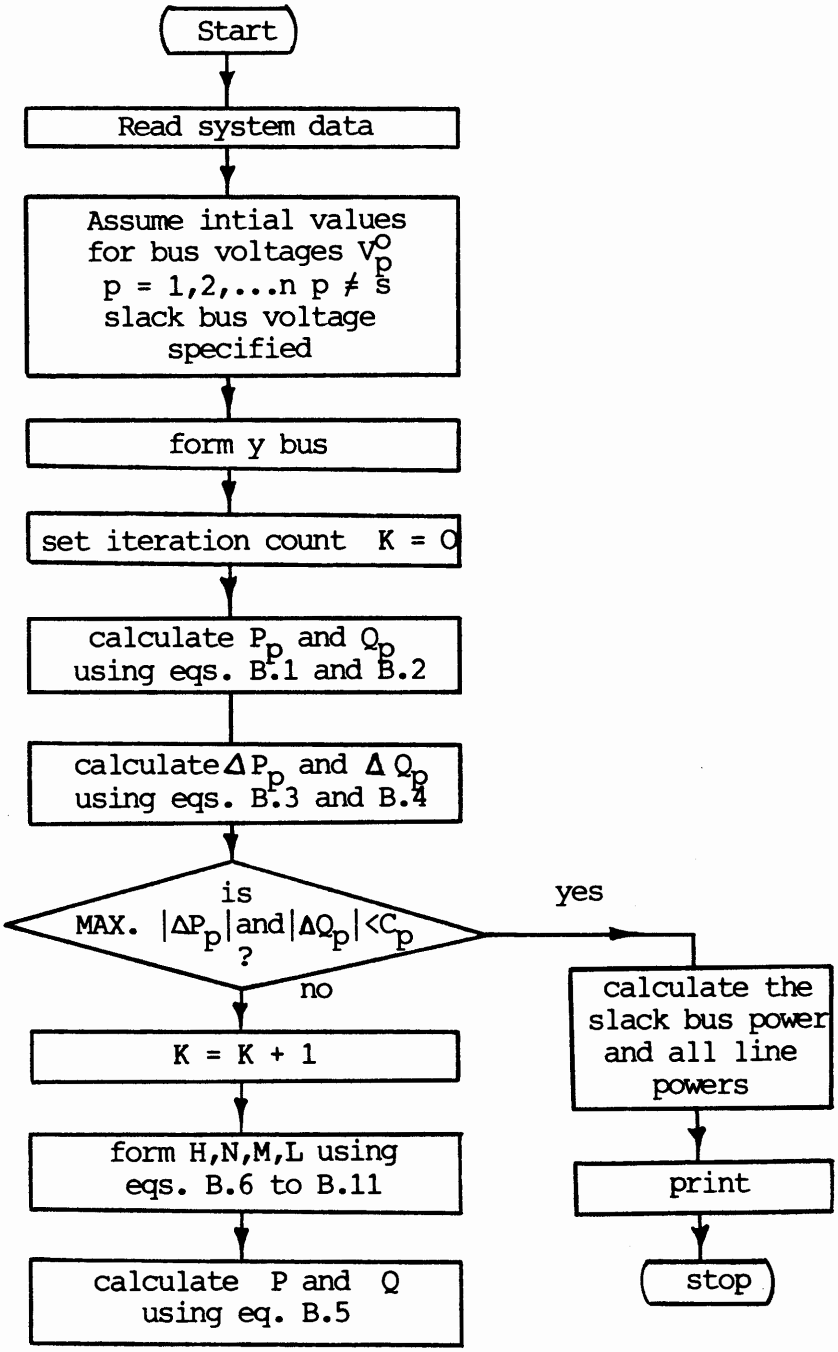
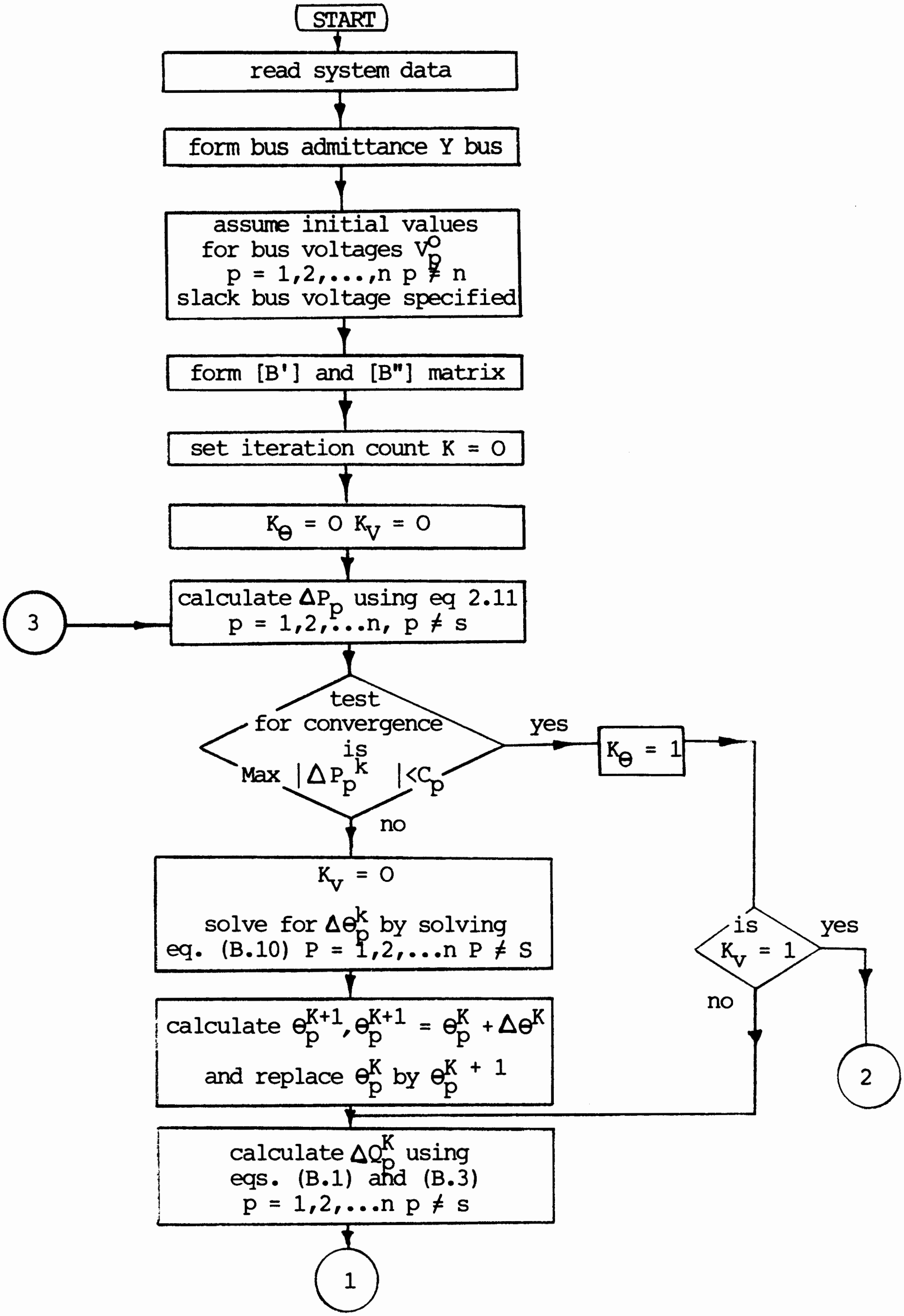


Figure 7. Flow chart for load flow studies using Newton Raphson Method.


START
read system data
form bus admittance Y bus
assume initial values for bus voltages V_p^o p = 1,2,...,n p ≠ n slack bus voltage specified
form [B'] and [B"] matrix
set iteration count K = 0
$K_\theta = 0$ $K_V = 0$
calculate ΔP_p using eq 2.11 p = 1,2,...n, p ≠ s
3
test for convergence is Max $|\Delta P_p^k| < C_p$
yes
no
$K_\theta = 1$
$K_V = 0$
solve for $\Delta\theta_p^k$ by solving eq. (B.10) P = 1,2,...n P ≠ S
calculate θ_p^{K+1}, $\theta_p^{K+1} = \theta_p^K + \Delta\theta^K$ and replace θ_p^K by θ_p^{K+1}
is $K_V = 1$
yes
no
2
calculate ΔQ_p^K using eqs. (B.1) and (B.3) p = 1,2,...n p ≠ s
1

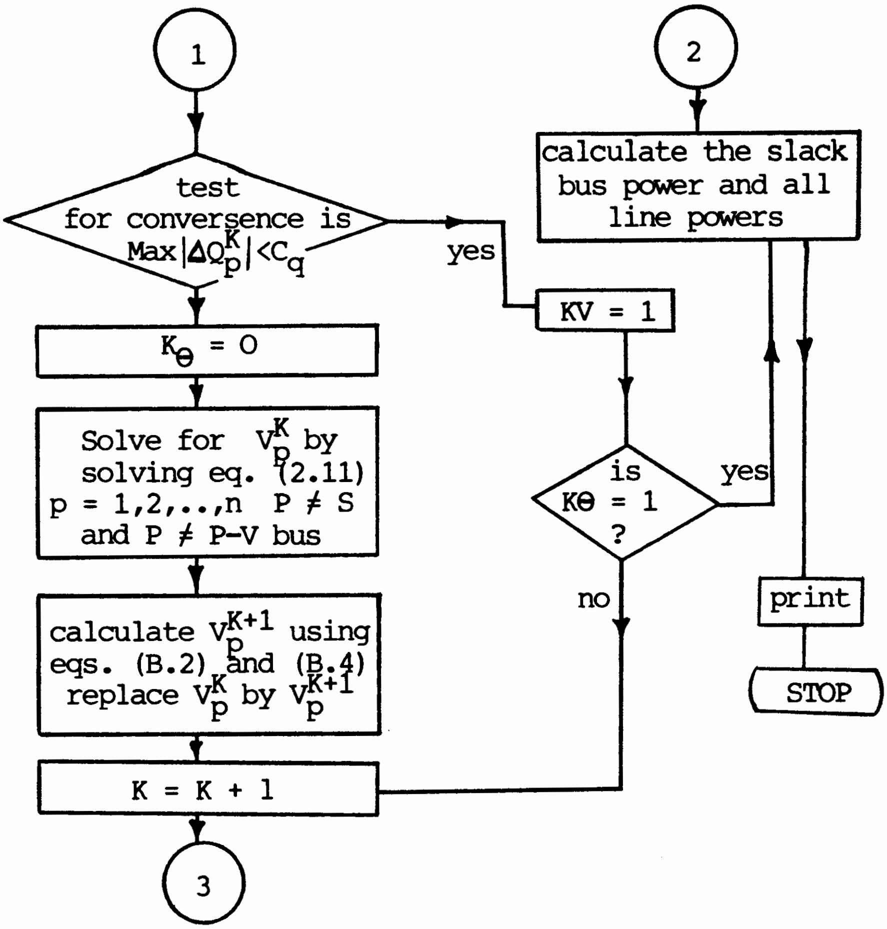


Figure 8. **Flow chart for load flow studies using fast decoupled technique**

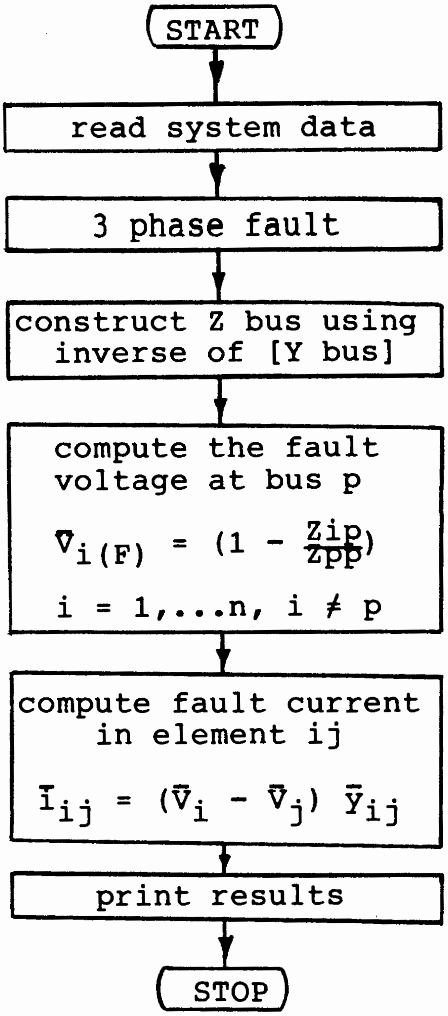


Figure 9. **Flow chart for three phase fault studies**

APPENDIX D

IEEE 14 BUS SYSTEM DATA

Line Designation	Resistance p.u.	Reactance p.u.	Line charging p.u.
1 - 2	0.01938	0.05917	0.0261
1 - 5	0.05403	0.22305	0.0246
2 ~~1~~ - 3	0.04699	0.19797	0.0219
2 - 4	0.05811	0.17632	0.0187
2 - 5	0.05695	0.17388	0.0170
3 - 4	0.06701	0.17102	0.0173
4 - 5	0.01335	0.04211	0.0064
4 - 7	0.0	0.20912	0.0
4 - 9	0.0	0.55618	0.0
5 - 6	0.0	0.25202	0.0
6 - 11	0.0498	0.19890	0.0
6 - 12	0.12291	0.25581	0.0
6 - 13	0.06615	0.13027	0.0
7 - 8	0.0	0.17615	0.0
7 - 9	0.0	0.11001	0.0
9 - 10			
9 - 14	0.12711	0.27038	0.0
10 - 11	0.08205	0.19207	0.0
12 - 13	0.22092	0.19988	0.0
13 - 14	0.17093	0.34802	0.0

Impedance and line charging susceptance is per unit on a 100 MVA base.
Line charging one-half of total charging of line

TABLE I

IMPEDANCE AND LINE CHARGING DATA FOR IEEE 14 BUS SYSTEM

Bus Number	Generation		Load	
	MW	MVAR	MW	MVAR
1*	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	94.2	19.0
4	0.0	0.0	47.8	-3.9
5	0.0	0.0	7.6	1.6
6	0.0	0.0	11.2	7.5
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	29.5	16.6
10	0.0	0.0	9.0	5.8
11	0.0	0.0	3.5	1.8
12	0.0	0.0	6.1	1.6
13	0.0	0.0	13.5	5.8
14	0.0	0.0	14.9	5.0

* indicates slack bus

TABLE II

GENERATION AND LOAD SCHEDULES FOR IEEE 14 BUS SYSTEM

Transformer designation	Tap setting
4 - 7	0.978
4 - 9	0.969
5 - 9	0.932

TABLE III

TRANSFORMER DATA FOR IEEE 14 BUS SYSTEM

Bus No.	PU Voltage	Q_{min}, MVAR	Q_{max} MVAR
2	1.045	-40	50
3	1.010	0	40
6	1.070	-6	24
8	1.090	-6	24

TABLE IV

REGULATED BUS DATA FOR IEEE 14 BUS SYSTEM

APPENDIX E

LOAD FLOW RESULTS

In this appendix the load flow results solved by Newton Raphson and Fast Decoupled methods are given.

```
***************************************************************************
--------------------> maximum error is 0.000717 <--------------------

----------------------> # of iterations was 3 <----------------------
***************************************************************************
```

Bus #	Voltage p.u.	Angle (degree)	MW	MVAR
1	1.060	0.000	232.30	-16.90
2	1.045	-4.992	18.31	29.62
3	1.010	-12.747	-94.19	4.36
4	1.019	-10.348	-47.77	3.95
5	1.020	-8.802	-7.57	-1.53
6	1.070	-14.255	-11.18	4.66
7	1.062	-13.399	0.02	0.05
8	1.090	-13.399	0.00	17.32
9	1.056	-14.980	-29.55	-16.58
10	1.051	-15.139	-0.01	-5.80
11	1.057	-14.829	-3.49	-1.79
12	1.055	-15.112	-6.10	-1.60
13	1.050	-15.193	-13.49	-5.79
14	1.036	-16.075	-14.91	-5.00

TABLE V

LOAD FLOW RESULTS BY NEWTON-RAPHSON METHOD FOR IEEE 14 BUS SYSTEM

BUS from	to	LINE FLOW MW	MVAR
1	2	156.83	-20.39
2	1	-152.54	27.66
1	5	75.55	3.50
5	1	-72.79	2.58
2	3	73.19	3.57
3	2	-70.87	1.58
2	4	56.14	-2.29
4	2	-54.46	3.39
2	5	41.51	0.76
5	2	-40.61	-1.63
3	4	-23.33	2.81
4	3	23.70	-5.42
4	5	-61.22	15.67
5	4	61.74	-15.37
4	7	28.09	-20.83
7	4	-28.09	23.24
4	9	16.09	-6.48
9	4	-16.09	8.04
5	6	44.06	-19.51
6	5	-44.06	24.75
6	11	7.34	3.47
11	6	-7.29	-3.36
6	12	7.78	2.49
12	6	-7.71	-2.34
6	13	17.74	7.17
13	6	-17.53	-6.75
7	8	0.00	-16.91
8	7	0.00	17.36
7	9	28.09	5.80
9	7	-28.09	-4.99
9	14	9.44	3.67
14	9	-9.32	-3.42
10	11	-3.77	-1.53
11	10	3.79	1.56
12	13	1.61	0.74
13	12	-1.60	-0.74
13	14	5.63	1.69
14	13	-5.58	-1.58
9	10	5.24	4.31
10	9	-5.23	-4.27

Losses in the system = 13.39,(27.99)

TABLE VI

LINE FLOW RESULTS BY NEWTON-RAPHSON METHOD FOR IEEE 14 BUS SYSTEM

BUS #	Reactive Flow (MVAR)
9	-21.20

TABLE VII

FLOW IN THE SHUNT ELEMENT RESULT BY NEWTON RAPHSON METHOD FOR IEEE 14 BUS SYSTEM

```
*******************************************************************
------------------> maximum error is 0.007385 <-------------------
--------------------> # of iterations was 7 <--------------------
*******************************************************************
```

Bus #	Voltage p.u.	Angle (degree)	MW	MVAR
1	1.060	0.000	232.39	-16.89
2	1.045	-4.992	18.30	29.69
3	1.010	-12.747	-94.20	4.39
4	1.019	-10.348	-47.79	3.91
5	1.020	-8.802	-7.60	-1.61
6	1.070	-14.254	-11.09	4.81
7	1.062	-13.399	0.00	0.00
8	1.090	-13.399	0.00	17.35
9	1.056	-14.981	-29.53	-16.62
10	1.051	-15.139	-8.99	-5.80
11	1.057	-14.828	-3.52	-1.81
12	1.056	-15.083	-6.88	-2.25
13	1.050	-15.204	-12.79	-5.18
14	1.036	-16.080	-14.89	-5.00

TABLE VIII

LOAD FLOW RESULTS BY FAST DECOUPLED METHOD FOR IEEE 14 BUS SYSTEM

BUS from	to	LINE FLOW MW	MVAR
1	2	156.83	-20.39
2	1	-152.54	27.66
1	5	75.55	3.50
5	1	-72.79	2.58
2	3	73.19	3.57
3	2	-70.87	1.58
2	4	56.14	-2.29
4	2	-54.46	3.39
2	5	41.51	0.76
5	2	-40.61	-1.63
3	4	-23.33	2.81
4	3	23.70	-5.42
4	5	-61.23	15.67
5	4	61.74	-15.37
4	7	28.09	-20.83
7	4	-28.09	23.24
4	9	16.09	-6.48
9	4	-16.09	8.04
5	6	44.06	-19.51
6	5	-44.06	24.75
6	11	7.34	3.47
11	6	-7.29	-3.36
6	12	7.54	2.43
12	6	-7.48	-2.29
6	13	17.93	7.22
13	6	-17.72	-6.79
7	8	0.00	-16.91
8	7	0.00	17.36
7	9	28.09	5.80
9	7	-28.09	-5.00
9	14	9.47	3.68
14	9	-9.35	-3.43
10	11	-3.78	-1.53
11	10	3.80	1.56
12	13	1.93	0.69
13	12	-1.92	-0.69
13	14	5.60	1.68
14	13	-5.54	-1.57
9	10	5.23	4.31
10	0	-5.22	-4.27

Losses in the system = 13.39,(27.99)

TABLE IX

LINE FLOW RESULTS BY FAST DECOUPLED METHOD FOR IEEE 14 BUS SYSTEM

BUS #	Reactive Flow (MVAR)
9	-21.20

TABLE X

FLOW IN THE SHUNT ELEMENT RESULT BY FAST DECOUPLED METHOD FOR IEEE 14 BUS SYSTEM

APPENDIX F

CONTINGENCY ANALYSIS RESULTS

In this appendix the network outage Contingency Analysis results for IEEE 14 Bus System are given

Bus #	Voltage p.u.	Angle (degree)	MW	MVAR
1	1.060	0.000	229.85	-14.46
2	1.045	-4.908	19.37	33.67
3	1.010	-12.553	-93.23	6.63
4	1.014	-10.050	-49.19	4.15
5	1.016	-8.784	-7.33	-1.54
6	1.070	-15.820	-9.53	3.21
7	1.068	-13.899	0.30	0.10
8	1.090	-18.899	0.00	13.47
9	1.055	-18.882	-28.34	-16.61
10	1.049	-18.643	-9.11	-5.79
11	1.055	-17.400	-3.92	-1.80
12	1.053	-16.910	-7.87	-2.25
13	1.050	-17.076	-12.07	-5.18
14	1.035	-19.102	-14.89	-4.99

TABLE XI

NETWORK OUTAGE CONTINGENCY ANALYSIS RESULTS LINE OUTAGE FROM BUS 4 TO BUS 7 FOR IEEE 14 BUS SYSTEM

BUS from	to	LINE FLOW MW	MVAR
1	2	154.30	-19.80
2	1	-150.15	26.64
1	5	75.55	5.34
5	1	-72.78	0.82
2	3	72.20	3.66
3	2	-69.94	1.23
2	4	54.61	0.58
4	2	-53.02	0.28
2	5	42.71	2.79
5	2	-41.75	-3.46
3	4	-23.29	5.41
4	3	23.68	-7.95
4	5	-50.27	10.98
5	4	50.61	-11.21
4	9	30.41	-5.27
9	4	-30.41	10.26
5	6	56.58	-19.76
6	5	-56.58	27.93
6	11	15.90	0.58
11	6	-15.69	-0.14
6	12	9.53	2.42
12	6	-9.42	-2.20
6	13	21.63	5.42
13	6	-21.34	-4.85
7	8	0.00	-13.20
8	7	0.00	13.47
7	9	-0.30	13.10
9	7	0.30	-12.94
9	14	4.30	5.86
14	9	-4.24	-5.73
10	11	-11.66	-1.90
11	10	11.77	-1.66
12	13	1.56	0.04
13	12	-1.55	-0.05
13	14	10.83	0.37
14	13	-10.65	0.74
9	10	-2.53	7.74
10	9	2.55	-7.69

Losses in the system = 13.45,(30.91)

TABLE XII

LINE FLOW RESULTS OF LINE OUTAGE FROM BUS 4 TO BUS 7
FOR IEEE 14 BUS SYSTEM

BUS #	Reactive Flow (MVAR)
9	-21.14

TABLE XIII

FLOW IN THE SHUNT ELEMENT RESULT OF LINE OUTAGE
FROM BUS 4 TO BUS 7 FOR IEEE 14 BUS SYSTEM

```
*****************************************************************
--------------->maximum error is 0.008510<--------------------

----------------->#  of iterations was 7<---------------------
*****************************************************************
```

Bus #	Voltage p.u.	Angle (degree)	MW	MVAR
1	1.060	0.000	232.69	-14.86
2	1.045	-4.978	18.30	34.71
3	1.010	-12.686	-94.20	7.18
4	1.014	-10.128	-47.79	3.91
5	1.016	-8.872	-7.60	-1.61
6	1.070	-16.050	-11.10	3.51
7	1.068	-19.129	0.00	0.00
8	1.090	-19.129	0.00	13.51
9	1.054	-19.129	-29.53	-16.62
10	1.049	-18.875	-8.99	-5.79
11	1.055	-17.610	-3.52	-1.81
12	1.056	-17.039	-7.00	-2.35
13	1.049	-17.333	-12.67	-5.07
14	1.034	-19.355	-14.90	-5.00

TABLE XIV

LOAD FLOW RESULTS BY FAST DECOUPLED METHOD WITH LINE OUTAGE FROM BUS 4 TO BUS 7 FOR IEEE 14 BUS SYSTEM

BUS from	to	LINE FLOW MW	MVAR
1	2	156.40	-20.29
2	1	-152.13	27.48
1	5	76.29	5.43
5	1	-73.46	0.95
2	3	72.77	3.61
3	2	-70.47	1.43
2	4	54.72	0.69
4	2	-53.13	0.19
2	5	42.94	2.93
5	2	-41.97	-3.57
3	4	-23.72	5.75
4	3	24.13	-8.25
4	5	-49.78	11.04
5	4	50.12	-11.28
4	9	30.97	-5.18
9	4	-30.97	10.35
5	6	57.70	-19.76
6	5	-57.70	28.22
6	11	15.71	0.61
11	6	-15.51	-0.18
6	12	8.52	1.89
12	6	-8.44	-1.72
6	13	22.23	5.85
13	6	-21.93	-5.25
7	8	0.00	-13.26
8	7	0.00	13.53
7	9	0.00	13.26
9	7	0.00	-13.09
9	14	4.38	5.94
14	9	-4.32	-5.81
10	11	-11.90	-1.87
11	10	12.01	-1.62
12	13	2.98	0.12
13	12	-2.96	-0.11
13	14	10.76	0.44
14	13	-10.58	0.81
9	10	-2.88	7.72
10	9	2.90	-7.67

Losses in the system = 13.69,(32.20)

TABLE XV

LINE FLOW RESULTS BY FAST DECOUPLED METHOD WITH LINE OUTAGE FROM BUS 4 TO BUS 7 FOR IEEE 14 BUS SYSTEM

BUS #	Reactive Flow (MVAR)
9	-21.13

TABLE XVI

FLOW IN THE SHUNT ELEMENTS BY FAST DECOUPLED METHOD
WITH LINE OUTAGE FROM BUS 4 TO BUS 7 FOR IEEE BUS SYSTEM

APPENDIX G

RESULTS DUE TO A THREE-PHASE FAULT

In this appendix the bus voltages and line currents during a 3 phase fault are given

Faulted Bus is 5

BUS #	Fault Voltage magnitude p.u. (angle) (degree)
1	0.78(-1.236)
2	0.93(-1.363)
3	0.59(-4.155)
4	0.28(-3.626)
5	0.00(0.000)
6	0.18(9.253)
7	0.48(-2.458)
8	0.81(-0.541)
9	0.39(-4.524)
10	0.35(-3.633)
11	0.26(0.105)
12	0.19(7.930)
13	0.20(5.115)
14	0.31(-1.880)

TABLE XVII

BUS VOLTAGES DURING A 3-PHASE FAULT AT BUS 5

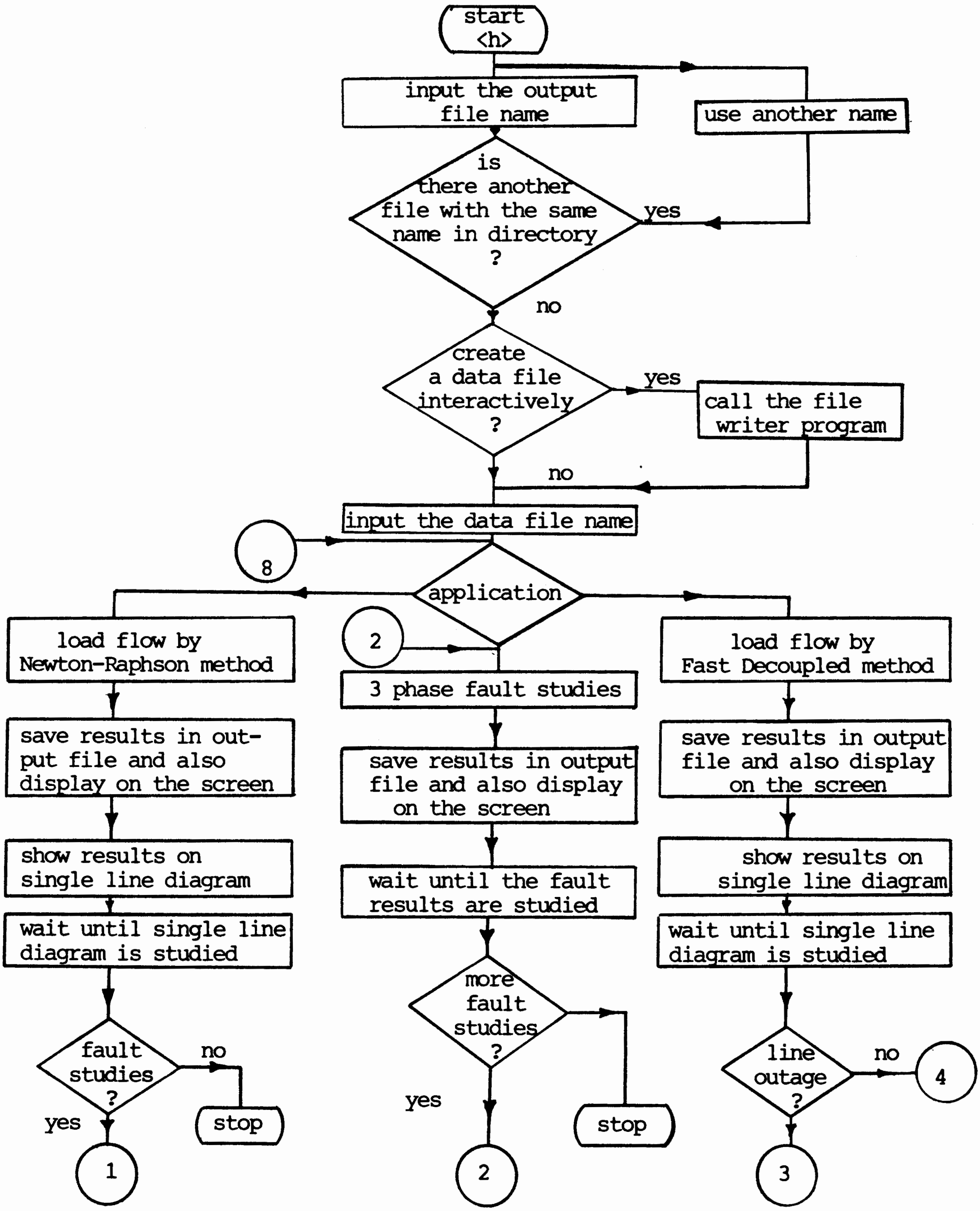
FOR IEEE 14 BUS SYSTEM

BUS from	BUS to	LINE FLOW current (p.u.)
1	2	2.335(-74.074)
2	1	2.335(105.926)
1	5	3.410(-77.792)
5	1	3.410(102.208)
2	3	1.683(-73.391)
3	2	1.683(106.609)
2	4	3.501(-72.316)
4	2	3.501(107.684)
2	5	5.072(-73.391)
5	2	5.072(106.609)
3	4	1.683(-76.200)
4	3	1.683(106.609)
4	5	6.300(-76.200)
5	4	6.300(103.800)
4	7	0.976(89.377)
7	4	0.976(269.337)
4	9	0.194(83.365)
9	4	0.194(263.365)
5	6	0.696(-80.951)
6	5	0.696(99.049)
6	11	0.423(-81.931)
11	6	0.423(98.069)
6	12	0.056(-71.358)
12	6	0.056(108.642)
6	13	0.218(-81.495)
13	6	0.218(98.505)
7	8	1.858(-87.918)
8	7	1.858(92.561)
7	9	0.885(-84.439)
9	7	0.885(95.561)
9	14	0.274(-79.435)
14	9	0.274(100.565)
10	11	0.423(-81.931)
11	10	0.423(98.069)
12	13	0.056(-71.358)
13	12	0.056(108.642)
13	14	0.274(-79.435)
14	13	0.274(100.565)
9	10	0.423(-81.931)
10	9	0.423(98.069)

TABLE XVIII

LINE CURRENTS DURING A 3-PHASE FAULT AT BUS 5

APPENDIX H


start
<h>
input the output file name
use another name
is there another file with the same name in directory ?
yes
no
create a data file interactively ?
yes
call the file writer program
no
input the data file name
8
application
load flow by Newton-Raphson method
2
3 phase fault studies
load flow by Fast Decoupled method
save results in output file and also display on the screen
save results in output file and also display on the screen
save results in output file and also display on the screen
show results on single line diagram
wait until the fault results are studied
show results on single line diagram
wait until single line diagram is studied
more fault studies ?
wait until single line diagram is studied
fault studies ?
no
yes
stop
1
yes
stop
2
line outage ?
no
4
3

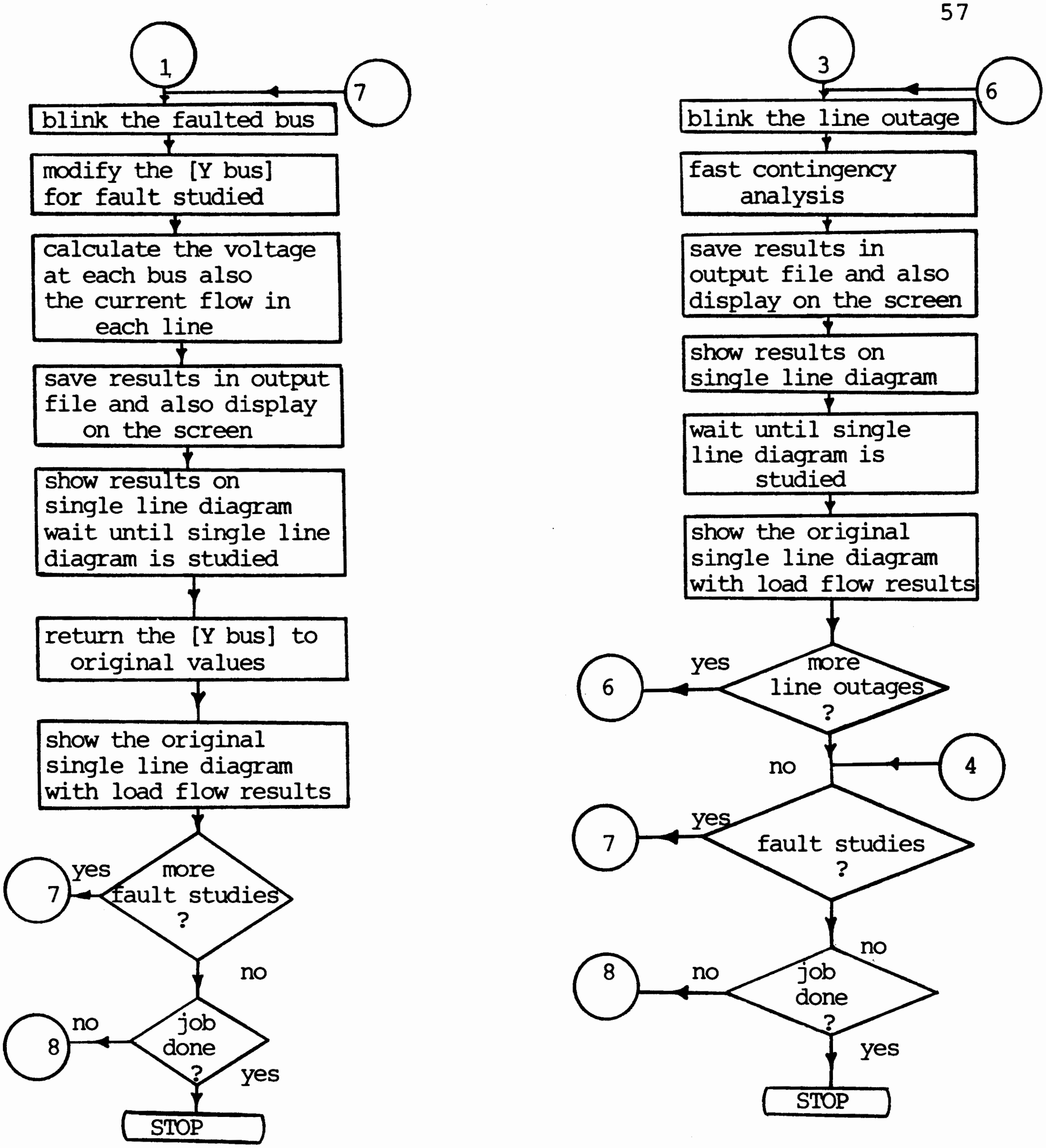


Figure 10. Block diagram of computer program